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Experimental verification of wave packet collapse using fourth-order interference

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Abstract

The concept of wave packet collapse is the most interesting and difficult to understand assumption of quantum mechanics and it remains an unresolved issue. Therefore, it is necessary to carefully examine its principle and process experimentally. We fabricated a new fourth-order interference apparatus capable of verifying the collapse of a wave packet. Contrary to expectation, a "collapse" was not observed in our experiment.

***Keywords*:** wave packet collapse, fourth-order interference, double slit, fringes

1. Introduction

Quantum mechanics has correctly explained phenomena that are difficult to understand intuitively. A typical example is wave–particle duality through double slit experiment using photons [1]. Intuitively understanding the behavior of photons in this experiment provides two important foundations of quantum mechanics: First, the superposition principle, which is evident from the experimental fact that interference of photons is not observed when particles pass through only one of the slits; The second is the assumption of the wave packet collapse, which was introduced to understand the fact that particles behave as if they passed through two slits but it is impossible to detect them simultaneously in both slits [2,3].

The collapse of a wave packet is the most interesting and difficult to understand assumption in the theory of quantum mechanics. This problem was initially raised by von Neumann, and thereafter, there has been no progress in building the theory of the collapse; it remains a difficult and unresolved issue [4]. This problem is extremely important not only in quantum mechanics but also in quantum computing and quantum communication [5], and it may introduce a limit in quantum computation and information processing speed.

Regarding the wave–particle duality, recently we reported [6] that the Englert–Greenberger duality relation [7] does not hold and suggested that re-examination will be necessary for the interpretation of duality. In this paper, we report an experimental apparatus capable of verifying the wave packet collapse and the results of our experiment.

2. Fourth-order interference

It is known that independent light sources do not have normal secondary interference, but exhibit fourth-order nonclassical interference effects. Mandel and co-workers [8] observed the interference between signal and idler photons obtained through parametric down-conversion by measuring the simultaneous detection probability of two photons at two spatially separated points and proved the existence of the nonclassical effect. Figure 1(a) shows the modified optical system applying their optical arrangement. The light beams emitted by the two independent light sources pass through the slits A and B, respectively, and are diffracted and split into two optical paths by the beam splitter BS (the equivalent optical system is shown in Fig. 1 (b)).

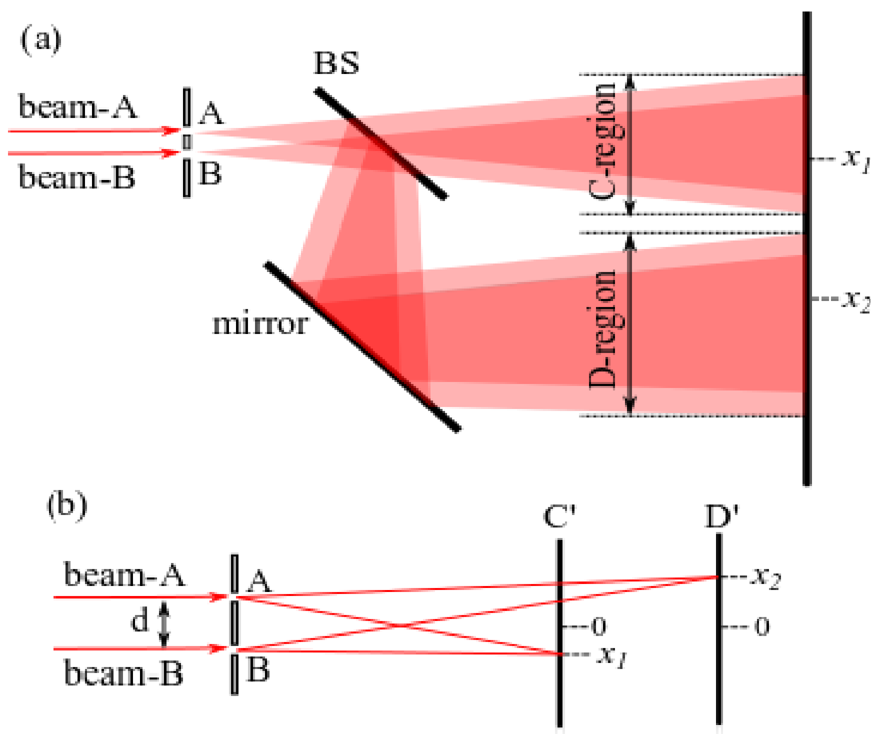

Fig. 1 (a) Optical system for observing fourth-order interference obtained in simultaneous measurement of photons in two spatially separated regions C and D, (b) schematic drawing equivalent to (a)

Let us consider a case where a photon is detected by each detector placed at x_1 and x_2. The positive frequency parts of the field at x_1 and x_2 are given by the following expressions:

$$\begin{aligned}\hat{E}^{(+)}(x_1) &= \hat{a}_A e^{i\boldsymbol{k}_{AC}\cdot\boldsymbol{r}_{A1}} + \hat{a}_B e^{i\boldsymbol{k}_{BC}\cdot\boldsymbol{r}_{B1}+i\delta} \\ \hat{E}^{(+)}(x_2) &= \left(\hat{a}_A e^{i\boldsymbol{k}_{AD}\cdot\boldsymbol{r}_{A2}} + \hat{a}_B e^{i\boldsymbol{k}_{BD}\cdot\boldsymbol{r}_{B2}+i\delta}\right) e^{i\delta_L}\end{aligned} \tag{1}$$

Here, $\boldsymbol{k}_{AC}$, $\boldsymbol{k}_{BC}$, $\boldsymbol{k}_{AD}$, $\boldsymbol{k}_{BD}$ are the wave vectors, $\boldsymbol{r}_{A1}$, $\boldsymbol{r}_{B1}$, $\boldsymbol{r}_{A2}$, $\boldsymbol{r}_{B2}$ are displacements, $\hat{a}_A, \hat{a}_B$ are photon annihilation operators, and δ, δ_L are phase differences of the beam and phase change due to reflection, respectively. In the case of the two-photon state, $|1_A,1_B>$ [8, 9], the probability $P_{12}(x_1,x_2)$ of simultaneous measurement at the positions x_1 and x_2 is

$$P_{12}(x_1,x_2) = K_1 K_2 \left\langle \hat{E}^{(-)}(x_1)\hat{E}^{(-)}(x_2)\hat{E}^{(+)}(x_2)\hat{E}^{(+)}(x_1)\right\rangle \tag{2}$$

where K_1 and K_2 are the scale factor characteristics of the detectors. Using Eq. (1)

$$\begin{aligned}P_{12}(x_1,x_2) &= K_1 K_2 \{1+\cos[(\boldsymbol{k}_{AC}\cdot\boldsymbol{r}_{A1} - \boldsymbol{k}_{BC}\cdot\boldsymbol{r}_{B1}) - (\boldsymbol{k}_{AD}\cdot\boldsymbol{r}_{A2} - \boldsymbol{k}_{BD}\cdot\boldsymbol{r}_{B2})]\} \\ &\approx K_1 K_2 \left\{1+\cos 2\pi\frac{d}{\lambda}\left(\frac{x_1}{L_1}-\frac{x_2}{L_2}\right)\right\}\end{aligned} \tag{3}$$

is obtained and it shows the fourth-order interference. Here, L_1 is the distance from the slit to the surface C' in Fig. 1 (b), L_2 is the distance from the slit to the surface D', d is the interval between the slits, and λ is the wavelength. The details of the derivation of the formula are described in Ref. [10]. It is a nonclassical feature that the visibility becomes 100% according to Eq. (3).

If two photons are emitted from one laser and detected one by one using each detector, the state is represented by $|2_A,0_B>$ or $|0_A,2_B>$, and the probabilities $P_A(x_1,x_2)$ and $P_B(x_1,x_2)$ are given by the following equations, respectively:

$$\begin{aligned}P_A(x_1,x_2) &= K_1 K_2 \\ P_B(x_1,x_2) &= K_1 K_2\end{aligned} \tag{4}$$

Equation (4) indicates a uniform intensity distribution and thus, no interference occurs owing to the emission of two photons from one laser.

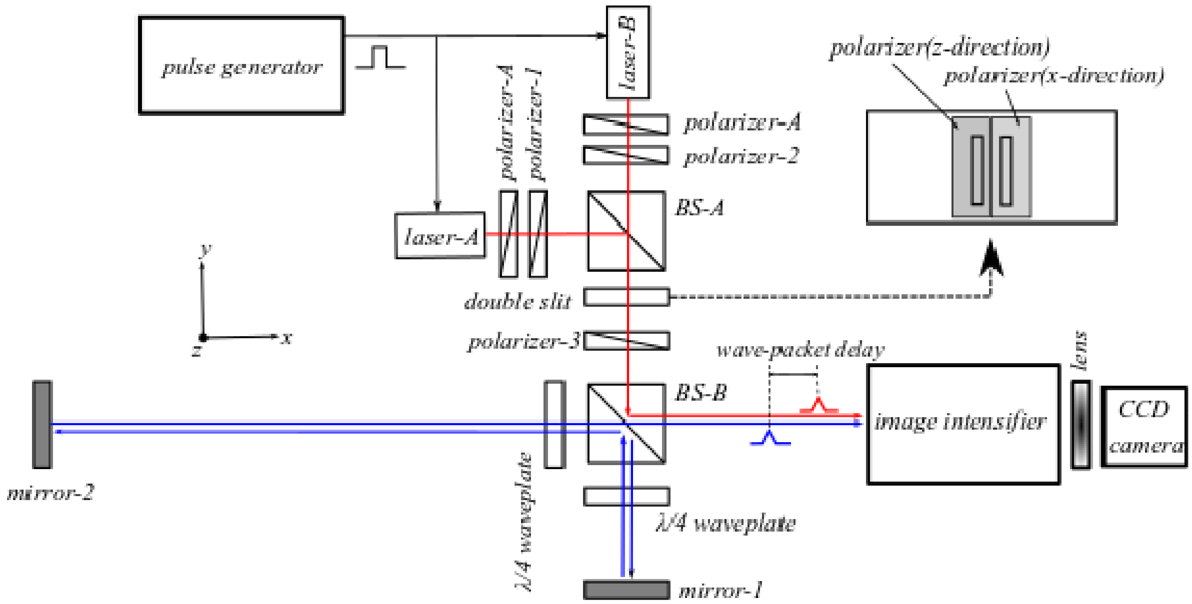

Fig. 2 Apparatus for observing fourth-order interference using short optical path (red) and long optical path (blue). A wave packet of approximately 4 ns is emitted from the independent light sources (laser-A and laser-B) using the pulse generator. The polarizing plate is arranged so that each light wave passes through only one of the double slits. Wave packets are divided by the polarizing beam splitter BS-B into a short optical path and a long optical path, and they enter the image intensifier.

3. Experiments

Figure 2 shows a schematic diagram of the apparatus. Laser-A and laser-B are semiconductor lasers with a wavelength of 635 nm and they output pulsed light with a width of approximately 4 ns. Each light is adjusted in intensity using polarizer-A and it enters the non-polarizing beam splitter BS-A through polarizer-1 (z-direction) and polarizer-2 (x-direction). The optical axis of the light is aligned with BS-A and the light incident on the double slit (interval = 0.5 mm, slit width = 0.2 mm). As the slit on the left side of the double slit is attached to the z-direction polarizing plate and the slit on the right side is attached to the x-direction polarizing plate, light from laser-A passes through only the left slit and light from laser-B passes through only the right slit. Polarizer-3 is fixed in the polarization of xz-direction (45°), and the component of the wave packet polarized in the z direction is reflected by the polarizing beam splitter BS-B and enters the image intensifier (HAMAMATSU C2400). The component of the wave packet polarized in the x-direction passes through the following optical path—λ/4 waveplate → mirror-1 → λ/4 waveplate → BS-B → λ/4 waveplate → mirror-2 → λ/4 waveplate → BS-B—and enters the image intensifier. The optical path length is adjusted by the position of mirror-2. Figure 3 shows the waveforms of the wave packet that passed through the short optical path P0 (red line in Fig. 2) and the long paths P1 and P2 (blue line). The optical path lengths of P1 and P2 are extended by 300 mm and 2180 mm, respectively, from that of P0. Here, L_1=510 mm, L_2=810 mm, and L_3=2690 mm. The inclination of the mirror-2 was adjusted so that the short optical path and the long optical path do not overlap each other.

Figure 4 shows the photon image obtained using the charge-coupled device (CCD) camera. The upper part is the image of the photon that passed through the long optical path (blue line in Fig. 2), and the lower part is the image of the photon that passed through the short optical path (red line in Fig. 2). Figure 4 (a) shows an image of the first detected photon pair, and Fig. 4 (b) is an image obtained by integrating approximately 200 pairs of photons. In the experiment, the pulse interval was set to 1/7 s and the frame rate of the CCD was set to 15 fps so that a light pulse did not affect multiple CCD images. Approximately 60,000 images (frames) were acquired to confirm the interference fringes. As the number of photons emitted from laser-A and laser-B cannot be controlled, the amount of light was limited so that the number of photons detected would be lower than 0.15 photons/frame (As the quantum efficiency of the image intensifier is approximately 10%, the actual number of emitted photons is approximately 1.5 photons/frame.). Consequently, the probability of obtaining a photon pair is very low (approximately 0.5%).

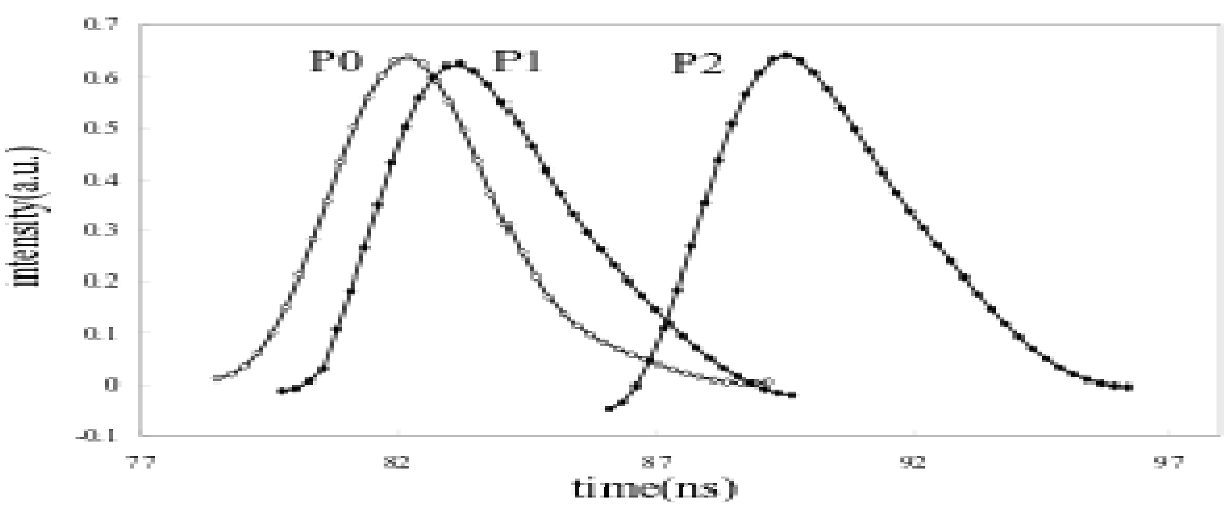

Fig. 3 Waveform of the wave packets P0, P1, and P2. P0 passes through a short optical path (red line in Fig. 2). P1 and P2 pass through a long optical path (blue line in Fig. 2). Optical path lengths of P1 and P2 are extended by 300 mm and 2180 mm, respectively, from that of P0.

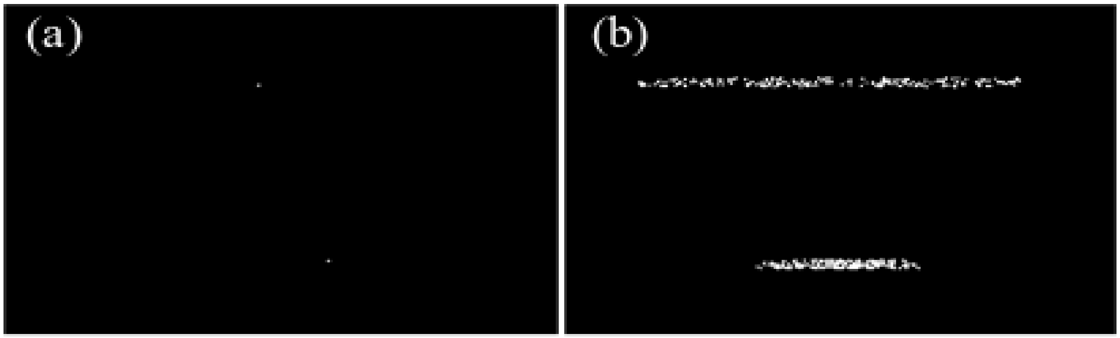

Fig. 4 Photon image obtained using a CCD camera. The photon that passed through a short optical path is displayed at the lower part of CCD and the one that passed through a long optical path is displayed at the upper part of CCD. (a) Image of one photon pair, (b) image of approximately 200 photon pairs.

4. Results and discussion

We first verified that the fourth-order interference is not observed using one laser, which is expected from Eq. (4). Using wave packets P0 and P1, each photon is detected at the lower and upper areas of the CCD. From the coordinates of each photon, the relative separation (x_1/L_1-x_2/L_2) is calculated. The count rate versus (x_1/L_1-x_2/L_2) is shown in Fig. 5 (normalized so that the maximum value is 1). No interference fringes were observed, which is evident from Eq. (4).

Figure 6 shows the count rate versus (x_1/L_1-x_2/L_2) using both laser-A and laser-B with the combination of wave packets P0 and P1. Apparent fourth-order interference fringes were obtained, which is expected from Eq. (3). As this interference fringe is a combination of Eqs. (3) and (4), the visibility is less than 100%.

Subsequently, we experimented with a combination of P0 and P2 using both lasers. Figure 7 shows a schematic diagram of the relative positions of P0 and P2. A wave packet P0 with a short optical path arrives at the detector before the photon in the wave packet P2 does. For example, in Fig. 7, if a photon in the wave packet (A) emitted from laser-A is detected by a detector, the wave packet (A') will collapse at that moment. Therefore, the second expression in Eq. (1) must be transformed as follows:

$$\hat{E}^{(+)}(x_2) = \hat{a}_B e^{i\boldsymbol{k}_{B2}\cdot\boldsymbol{r}_{B2}} \tag{5}$$

and fourth-order interference fringes will not be obtained. The same result is obtained when the photon emitted from laser-B is detected first. Thus, it is predicted that fourth-order interference would not occur with the combination of wave packets P0 and P2. However, as shown in Fig. 8, interference fringes were observed. Although the fringes were slightly deformed, sufficiently recognizable interference fringes were observed and the visibility was the same as in Fig. 6.

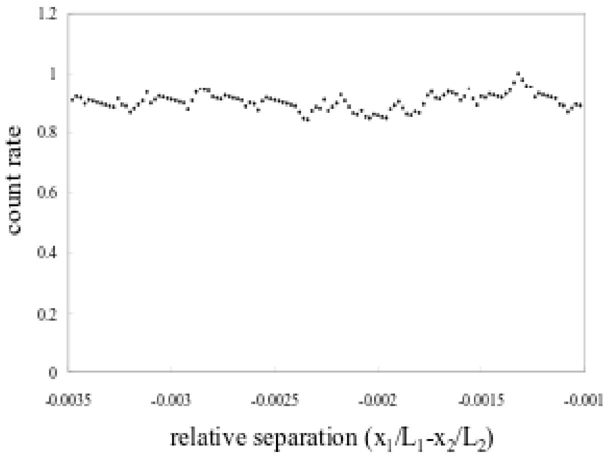

Fig. 5 Count rate obtained for wave packets P0 and P1 versus relative separation (x_1/L_1-x_2/L_2) using only laser-A (normalized so that the maximum value is 1). Interference fringes were not obtained.

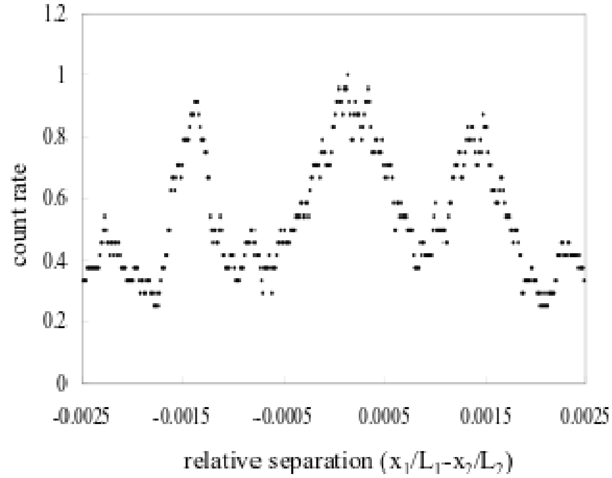

Fig. 6 Count rate obtained for wave packets P0 and P1 versus relative separation (x_1/L_1-x_2/L_2) using both laser-A and laser-B (normalized so that the maximum value is 1). Apparent interference fringes were observed.

Low quantum efficiency of the detector may cause problems in the counting of photons. The quantum efficiency of the image intensifier of the present apparatus is approximately 10%. In the experiment, approximately 60,000 images were captured and only the image that detected the photon pair was used for the analysis. However, as the quantum efficiency is low, there is a possibility that three or more photons are contained in the image intensifier. In order to avoid this, the light intensity was adjusted so that the average number of photons of an image was less than 0.15. Even when considering the quantum efficiency of 10%, the number of photons incident on the image intensifier per imaging is 1.5 on average. Moreover, as the ratios of detection count are (three photon / two photon) = 0.1 and (four photon / two photon) = 0.01, the visibility of the interference fringes in Fig. 8 cannot be explained by the detection of three or more photons.

The collapse of the wave packet is a concept indispensable to the theoretical system in the Copenhagen interpretation. On one hand, there are reports supporting it (for example, experiments of Aspect [11, 12]); on the other hand, there are reports skeptical of the series of experiments related to Bell's inequality [13]. Our experiment was conducted to "capture" the wave packet collapse and to examine its process, but the experiment resulted in denying the "collapse" of the wave packet.

The locality is loophole in "Bell test experiments", and long distance (over 1 km) experiment was conducted to avoid this problem. In this experiment, it is assumed that collapse of wave packet occurs instantaneously. However, when a finite amount of time is required to collapse the wave packet, a sufficient time difference (difference in distance) between a long optical path and a short optical path is necessary. Therefore, if the time difference between the two wave packets is increased, collapse of the wave packet may be observed. We will further investigate whether there are loopholes in this experiment.

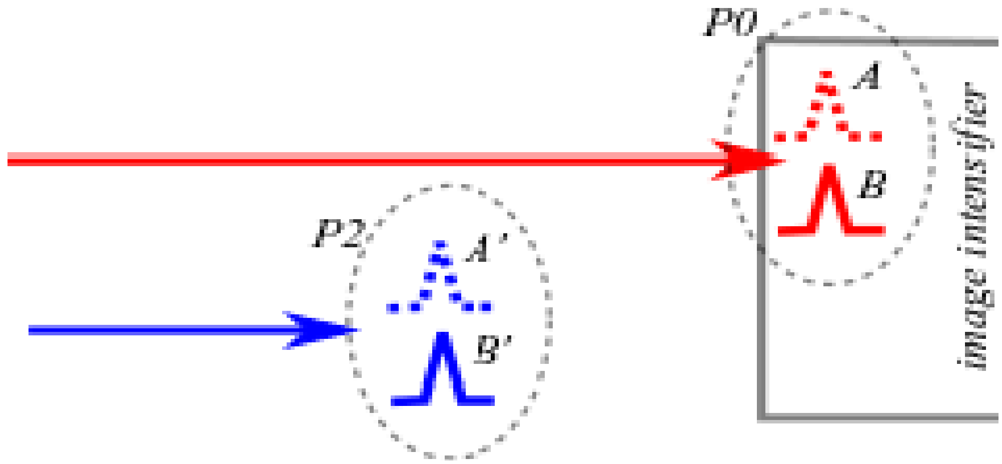

Fig. 7 Schematic diagram of the relative position of wave packets P0 and P2 at a certain time

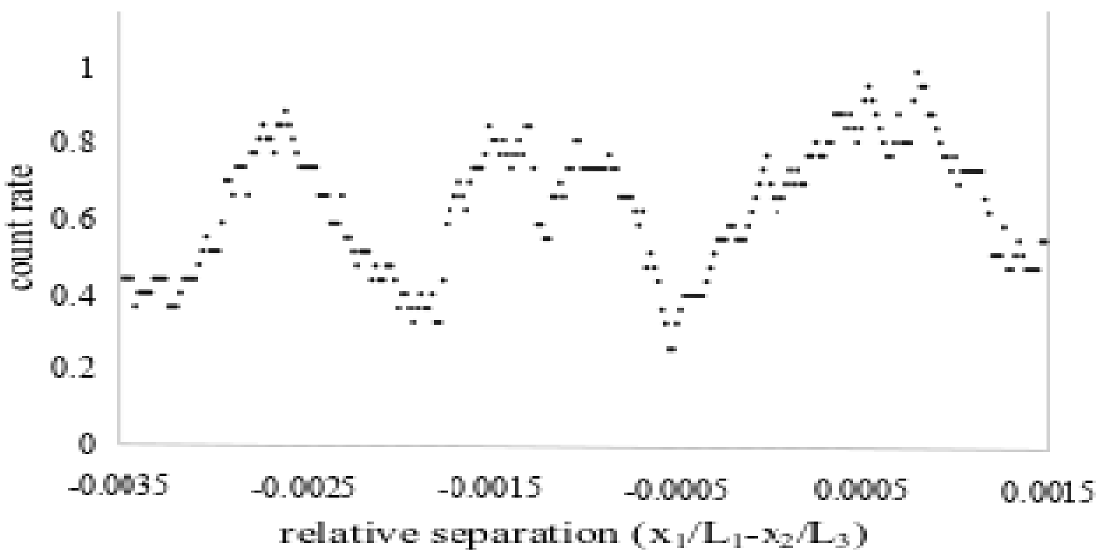

Fig. 8 Count rate obtained for wave packets P0 and P2 versus relative separation (x_1/L_1-x_2/L_3) using both laser-A and laser-B (normalized so that the maximum value is 1). Interference fringes were observed.

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